RELATING TIME TO THE EARTH'S VARIABLE ROTATION

H. Chadsey and D. McCarthy
U.S. Naval Observatory
Washington, DC 20392, USA

Abstract

With the beginning of the 21st Century, the timing community finds itself again facing a decades-old problem of how to synchronize a uniform time scale with time derived from the Earth's rotation. Atomic time is the basis for most everyday timing applications. However, time astronomically determined from the Earth's rotation is essential for other applications including navigation. The history of relating atomic time to the Earth's rotation is presented, including background information related to the current synchronization method of leap seconds.

INTRODUCTION

The technological advances of the 20th Century are causing the timing community to examine once again the decision to synchronize atomic time with the Earth's rotation using leap seconds. Historically, time scales in common use have been maintained to within at least 1 second of time derived from the Earth's rotation. The current practice is to insert 1-second adjustments, called leap seconds, into the atomic-based time scale to bring the two types of time to within 0.9 seconds of one another. These adjustments are made internationally, preferably at 23h 59m 59s on 30 June or 31 December depending on the varying rotation of the Earth. However, as technology advances, the time steps required to maintain that level of synchronization become more inconvenient for some users to implement. Before going into the details of leap second implementation, we should first look at the history of the second and leap seconds.

RECENT HISTORY OF THE DEFINITION OF THE SECOND

Two concepts for the definition of the second have been used in modern times. The first is the definition of a second based on the Earth's rotation with respect to the Sun. The second is based on the Earth's revolution about the Sun and is realized in practice by the frequency of an atomic transition in the cesium atom.

ROTATIONAL SECOND

Throughout history, the definition of time has traditionally been related to repetition of solar phenomena such as successive sunrises, sunsets or transits of the local meridian. In modern times, the astronomical second was defined conventionally as 1/86400 of the time required for

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **NOV 2000**	2. REPORT TYPE	3. DATES COVERED **00-00-2000 to 00-00-2000**
4. TITLE AND SUBTITLE **Relating Time to the Earth's Variable Rotation**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **U.S. Naval Observatory,Washington,DC,20392**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM001509. 32nd Annual Precise Time and Time Interval (PTTI) Meeting, 28-30 Nov 2000, Reston, VA

14. ABSTRACT
With the beginning of the 21st Century, the timing community finds itself again facing a decades-old problem of how to synchronize a uniform time scale with time derived from the Earth?s rotation. Atomic time is the basis for most everyday timing applications, However, time astronomically determined from the Earth?s rotation is essential for other applications including navigation. The history of relating atomic time to the Earth?s rotation is presented, including background information related to the current synchronization method of leap seconds.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**18**	

an average rotation of the Earth on its axis with respect to the Mean Sun (the mean solar day). Although the variability of the Earth's rotational speed had been established in the 1930s [1,2], this definition of the second was generally accurate enough for the technology and time applications of the day. However, by 1956, the need for a more uniform time scale was recognized.

ATOMIC SECOND

The need for a second that was not dependent on the variable rotation of the Earth prompted the definition of a new "ephemeris second" determined by astronomical means. It was defined as 1/31,556,925.9747 of the tropical year at 12:00 hours Ephemeris Time on 0 January 1900 (i.e., 31 December 1899) [3,4]. The numerical value of the defining fraction was obtained from Simon NewcombÐs equation for the apparent motion of the Sun. However, operational measurement of the ephemeris second was available only retrospectively as an average of several years' continuous observations of the Moon's position. One major drawback to the ephemeris definition was that only astronomers could measure it directly.

The development of atomic clocks made it possible to access this ephemeris second more easily. Observations of the position of the Moon with respect to the stars made it possible to calibrate an atomic transition in the cesium atom in terms of the ephemeris second. The atomic second was adopted in October 1964 by the International Committee of Weights and Measures. They "declared that the transition to be used is that between the hyperfine levels F = 4, $m_F = 0$ and F = 3, $m_F = 0$ of the ground state 2S1/2 of the atom of cesium, unperturbed by external fields, that the value 9,192,631,770 Hz is assigned to the frequency of this transition."[5] This has been the definition of the SI (Système International) second since 1967.

TIME SCALES

Having defined the length of 1 second, we can now examine the different time scales that have been formed using these seconds.

ROTATIONAL TIME SCALES

Rotational time scales are based on the astronomical observations of the Earth's rotation angle with respect to a quasi-inertial reference frame and related to mean solar time through an adopted mathematical expression. Greenwich Mean Time (GMT) was used to designate the local mean solar time along the Greenwich meridian. Before 1925 mean solar time was measured from noon. Beginning on 1 January 1925, however, by international agreement, mean solar time was measured from midnight. To distinguish between the two means of reckoning GMT, the terminology "Greenwich Civil Time" (GCT) was employed by some to refer to the measurement of mean solar time from midnight [6]. Eventually the name "Universal Time" (UT) was accepted to replace both GMT as a rotational time scale and GCT. GMT is still used in the United Kingdom to refer to the local civil time.

Improving accuracy in the measurement of UT made it desirable to distinguish among different versions of UT. UT0 is the time directly observed locally from star observations. It does not provide an accurate description of the Earth's rotation angle, since it is corrupted with local effects such as the motion of the vertical and the effects of the motion of the rotational pole

over the surface of the Earth (called polar motion). UT1 is UT0 corrected for polar motion as specified by data furnished by astronomical observations. UT1 is a true representation of the rotation of the Earth free from local effects. UT2 is UT1 corrected for annual and seasonal variations by means of a conventional formula. Neither UT0 nor UT2 are in common use today by the non-specialist. Coordinated Universal Time (UTC) was originally defined as the piecewise uniform scale that approximates UT2. It is currently used as a "stepped offset" scale and is derived by making leap second adjustments [7].

ATOMIC TIME SCALES

With the advent of atomic clocks, a number of time scales, making use of the second defined by the frequency of cesium, came into use. The A.1 time scale of the U.S. Naval Observatory, established officially on 1 January 1959 [8], was defined by setting A.1 equal to UT2 on 1 January 1958 at 00:00 GMT (UTC). It was derived from clock information from nine laboratories and eventually made available back to 15 June 1955. Contributors to the A.1 time scale sometimes referred to the output of their clocks as A.1. The A.1 time scale is now derived solely from USNO clocks. Similarly, other timing laboratories created atomic scales based on their atomic clocks. In 1971, the international community accepted the A.3 Bureau International de l'Heure (BIH) atomic time scale as the standard and this came to be known as International Atomic Time (TAI). The BIH atomic time scale, determined between July 1955 and 1971, may also be referred to as TAI [9].

EAL (Echelle Atomique Libre) is a free atomic time scale produced by an iterative algorithm using the weighted average of clock readings from laboratories spread around the world. The processing is currently done in deferred-time and in whole 1-month data blocks. TAI (International Atomic Time) is derived from EAL by adding a linear function of time with a convenient slope to ensure the accuracy of the TAI scale interval as determined from primary cesium frequency standards. (The length of a second is calibrated in TAI where it is not in EAL.) The frequency offset between EAL and TAI may be changed to maintain the accuracy of the length of the second [10].

COORDINATED UNIVERSAL TIME

Because the rotational second is variable in length, atomic time and rotational time got out of step with each other. As a result, time scales were created that steered atomic clocks to the astronomical time. Some of these never gained widespread acceptance for practical use. Universal Atomic Time (UAT) [11] was used to designate a piecewise uniform scale that approximates UT2 to within about 0.1 second. It is a "stepped offset" scale and is derived by making adjustments in offset and epoch from the uniform atomic time scale. Stepped Atomic time (SA) [11] was used to designate the piecewise uniform scale that approximates UT2 to within about 0.1 second. It is a "stepped offset" scale and is derived by making adjustments in offset.

In August, 1959, national agencies in the United States (U.S. Naval Observatory, Naval Research Laboratory, and National Bureau of Standards) and the United Kingdom (Royal Greenwich Observatory, National Physical Laboratory, General Post Office) along with radio stations that provided precise time in those countries (NBA, Canal Zone; WWV, Beltsville; WWVH, Hawaii; GBR and MSF, Rugby) agreed to coordinate time so that broadcast time signals would be synchronized to 1 millisecond (ms) [12]. Time pulses were to remain within 50 ms

of UT2. This was accomplished by coordinated fractional offsets in the frequency of cesium and occasional adjustments in epoch if required. As more agencies and broadcasting stations began to participate, the time emitted by the participating radio stations came to be known as Coordinated Universal Time (UTC) [9]. However, UTC was not strictly defined until 1965 when the Bureau International de l'Heure (BIH) defined it with respect to its atomic time scale.

Prior to 1960, clocks had been steered by individual observatories and laboratories to match the time determined from the Earth's rotation. In the United States, the USNO rotational time scale called "N2" was used as the scale to which clocks were steered from 1 April 1953 until 1 January 1956 [13]. After 1 January 1956, the USNO determination of UT2 was used as the time scale to which U.S. clocks were steered [14]. These steers were in the form of steps of the order of tens of milliseconds inserted occasionally through 1959. Beginning in 1960, a combination of frequency and step offsets was made to steer UTC to UT2. From 1969 on, no time steps were employed until UTC was redefined as of 1 January 1972 to be the time scale that uses leap seconds to keep UTC within 0.9 s of UT1.

Dr. Gernot Winkler and Dr. Louis Essen proposed the concept of leap seconds independently in 1968 at a meeting at the International Bureau of Weights and Measures (BIPM) [15]. Winkler proposed that integer steps of seconds replace the steps of 200 milliseconds used to keep UT2 within 100 milliseconds of astronomical time. The 200-millisecond steps were occurring too often and were too small to be entered into most systems. He drew an analogy to the concept of leap years in the Julian Calendar. Interestingly, in his original proposal, Winkler stated that the leap seconds could be introduced either whenever necessary or "on a fixed day, such as the 29th of February" [16].

The transition from adjusting the length of a second to using a second of uniform length and inserting leap seconds to account for the time difference was made on 1 January 1972. It was made in such a way that the start of the rotational second and the atomic second would coincide at 0h 0m 0s on 1 January 1972. Figure 1 displays the history of TAI-UTC showing the step changes in epoch as well as the adjustments in frequency.

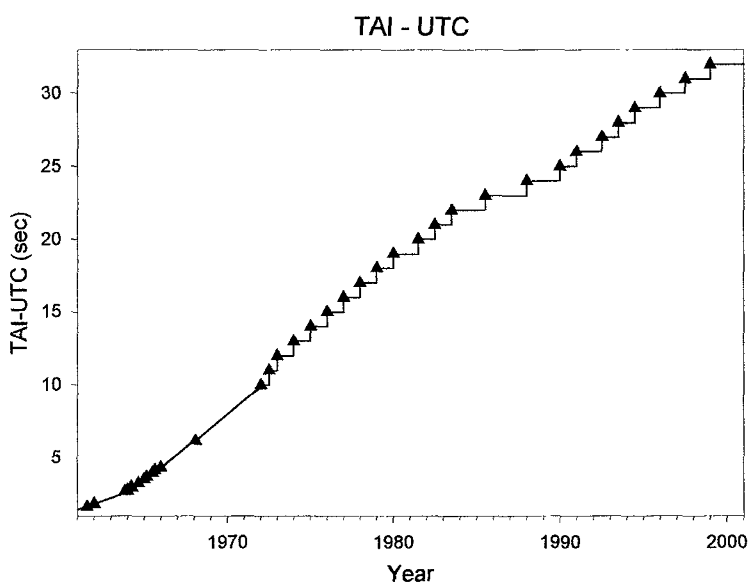

Figure 1. History of TAI-UTC showing the step changes in epoch as well as the adjustments in frequency.

CONSIDERATIONS REGARDING LEAP SECONDS

Naturally, the first consideration for keeping a uniform time synchronized to the Earth's rotation is navigation. The original reason for needing precise time was navigation at sea. Longitude determination requires one to know the correct time at a known location and at the location in question simultaneously. This was such an important issue in the early 1700s that the British government offered substantial rewards for anyone able to build a clock with a specified precision. Today, with GPS, GLONASS, LORAN, and other electronic navigation systems, celestial navigation is not as common. However, keeping the atomic time and Earth rotation synchronized is important to astronomers and others working with non-electronic-based navigation.

Another important consideration is the growing use of computers. In these applications time is independent of the Earth's orientation and problems can occur whenever a leap second is introduced into time systems. In today's world of high-speed inter-computer communications that time-stamp messages at the sub-second level, 1 second can be a significant length of time. In addition, clocks normally count from 59 seconds to 0 seconds of the next minute. Leap seconds require that the count is 59 seconds, 60 seconds, and then 00 seconds of the next minute. Many computer systems have a problem introducing the second labeled "60."

A third consideration is the legal definition of time. For example, legal time in the United States is based on mean solar time. UTC suitably adjusted for time zones is considered to be an adequate representation. Should the definition of UTC be revised, the effect on legal codes may need to be investigated.

Another concern that is sometimes raised is the effect on religious observances that are related to time synchronized to Earth rotation. Generally religions base make use of tables suited for their general location to coordinate observances. Those tables are produced with 1-minute accuracy. Some believers may choose to play it safe by waiting an extra 4 or 5 minutes to account for any irregularities in the tables and refraction of light.

Although there may not be a leap second in the next year, the Earth's deceleration is well documented and will not stop. It is due to the tides and change in the Earth's figure. Figure 2 shows the difference between UT1 and a uniform time scale. We can clearly see that the difference will continue to grow in the future with a rate larger than the current rate. Because the Earth will continue to decelerate, the frequency of leap seconds will increase producing increasing public annoyance. The insertion of leap seconds will also remain essentially unpredictable requiring continuous time counting systems such as computers to handle 86,401-second days and to time stamp a second labeled "60" without large amounts of pre-scheduling notice.

OPTIONS

Several options are available. Some proposed solutions are presented here.

Status Quo

The status quo would require no changes to most operations and would provide a minimum of concerns to celestial navigators. On the other hand, as noted earlier, the frequency of the leap seconds will increase causing problems for communications and software. It may lead to the growth of systems based on independent time scales.

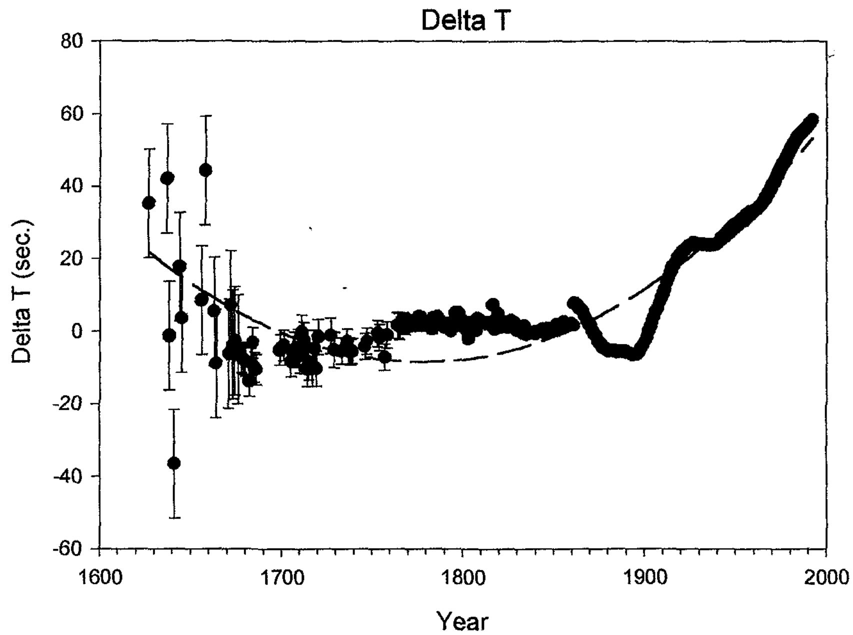

Figure 2. Observations of Delta T (UT1-Uniform Time) versus time. The thin broken line is a parabola fit to the observational data

Discontinue Leap Seconds

Leap seconds could be discontinued eliminating the cause for concern. However, there would be an unlimited growth in the difference between atomic and astronomical time (|UTC - UT1|). This could lead to major problems with civil law and the legal definitions of time.

Wider Use of International Atomic Time

Those needing a uniform time scale could use TAI instead of UT1. This would eliminate the concern, but TAI would have to be made much more accessible to users. Also, more of the general population would have to be educated about the existence of TAI and its use.

Redefine the Second

The length of the second could be redefined. This is a fundamental solution, but if it were done, it would require the redefinition of other physical units (e.g., length, force, and energy). Because the rotation of the Earth is decelerating, however, it would be necessary to continue to redefine the second periodically in the future.

Smoothing the Leap Second Occurrence

This option would require the length of seconds in the immediate neighborhood of the occurrence of a leap second to be changed so that there would be no "extra" second needed to adjust the uniform time by 1 second. This would, in effect, redefine the length of a second over a short period of time so the leap second would not appear. It would require seconds of different lengths, whose implementation process would have to be very clearly defined. The date of implementation would be unpredictable just as the insertion of leap seconds is currently.

Increase the Tolerance

The tolerance for |UTC - UT1| could be increased. This would be easy to accomplish. However, the size of the discontinuities (currently 1 second) would increase and possibly cause more serious problems then the present leap second system. The DUT1 codes have limitations and the magnitude of the differencewould have to be considered. The date of adjustment would be as unpredictable, and the acceptable limit may be difficult to establish.

Periodic Predictable Adjustments

UTC could be periodically adjusted by an unpredictable number of leap seconds on predictable dates based on an adopted deceleration model. The number of leap seconds inserted though could be unpredictable and large discontinuities would be possible. An extension of this possibility is that a known number of leap seconds could be inserted at predictable intervals. The date and number of leap seconds would be known. However, large discontinuities would be possible and |UTC - UT1| would be likely to be much greater than 1 second. Figure 3 shows a simulation of possible predictable adjustments. The simulation is based on the past observational history of TAI - UTC and shows that differences (UTC - UT1) on the order of 10 seconds would be expected if a plan were implemented in which periodic predicted adjustments were made to UTC based on the parabolic fit to the past history of UT1 - TAI.

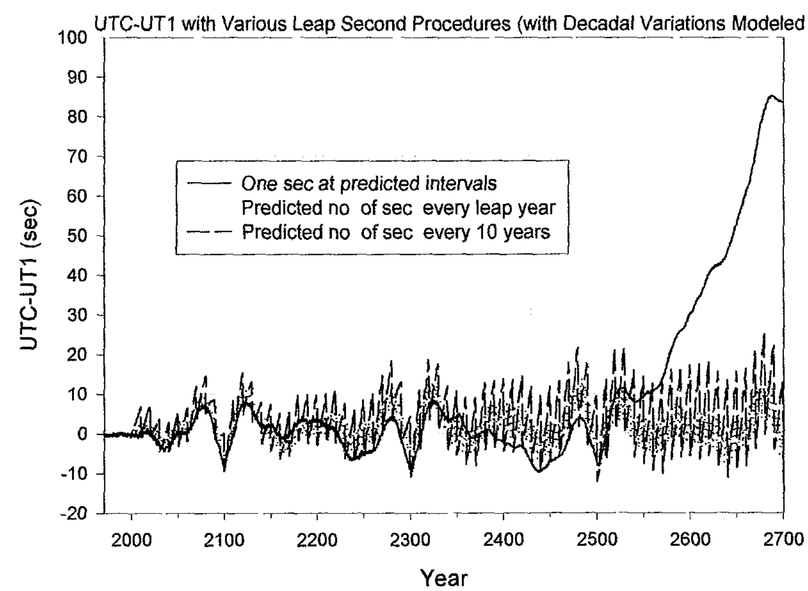

Figure 3. Simulation of expected UTC-UT1 showing the effects of different leap second insertion schemes.

CURRENT STUDY GROUPS

The International Union of Radio Science (URSI), the International Astronomical Union (IAU) and the International Telecommunications Union Radiocommunications Sector (ITU-R) are currently studying this topic. The ITU-R is expected to take the lead in formulating any possible changes to the current procedure.

REFERENCES

[1] H. Spencer Jones 1939, **Monthly Notices of the Royal Astronomical Society, 99,** 541-558.

[2] N. Stoyko 1937, *"Sur la periodicite dans l'irregularite de la rotation de la terra,"* **Comptes Rendues de l'Académie des Sciences, 205,** 79.

[3] **Transactions of the International Astronomical Union, IX,** Proceedings of the Ninth General Assembly, Dublin, Ireland, 1955, edited by P. Oosterhoff, Cambridge University Press, New York, New York, USA, 1956.

[4] *"The international system of units (SI),"* 7th edition, Bureau International des Poids et Mesures, Sèvres, France, 1998, p. 119.

[5] W. Markowitz, R. Hall, L. Essen, and J. Parry 1958, *"Frequency of cesium in terms of Ephemeris Time,"*, **Physical Review Letters, 1,** 105-107.

[6] **Transactions of the International Astronomical Union, III,** Third General Assembly, Leiden, Netherlands, 1928, edited by F. Stratton, Cambridge University Press, New York, New York, USA, 1929, p. 300.

[7] **Transactions of the International Astronomical Union, 10,** 1961, p. 489.

[8] *"Time Service notice no. 6,"* U.S. Naval Observatory, Washington, D.C., USA, 1959.

[9] B. Guinot 2000, *"History of the BIH,"* in **Polar Motion, Historical and Scientific Problems,** IAU Colloquium No. 178, edited by S. Dick, D. McCarthy, and B. Luzum, Astronomical Society of the Pacific Conference Series, 208, pp. 175-184.

[10] P. Seidelmann (editor) 1992, **Explanatory Supplement to the Astronomical Almanac,** revised edition, University Science Books, Mill Valley, California, USA, p. 85.

[11] G. Hudson 1972, *"Some characteristics of commonly used time scales,"* NBS Special Publication 300, Vol. 5, pp. 224-230.

[12] **Transactions of the International Astronomical Union, XIA-Reports,** edited by D. Sadler, Academic Press, New York, New York, USA, 1962, p. 363.

[13] Reference [10], p. 87.

[14] *"Time Service notice no. 4,"* U.S. Naval Observatory, Washington, D.C., USA, 1956.

[15] G. Winkler 2000, private communication.

[16] G. Winkler 1968, *"The future of international standards of frequency and time,"* memorandum submitted to the Ad Hoc Group meeting at the International Bureau of Weights and Measures (BIPM).

Discussion

RONALD BEARD (NRL): Good morning. As many of you are aware, the ITU is the international organization that regulates many of the things that relate across the different countries and organizations that require coordination. Such things as radio spectrum, telecommunication standards, and many of these things that are required for nations, companies, organizations, and systems to work together. You may also be aware that time and frequency broadcast services in the nations are also based on recommendations of the ITU-R. Within the ITU-R, Study Group VII, Science Services has established a working party, 7A, which looks at and recommends time and frequency services in relationships to time that are broadcasted by these services and their relationships to different time scales.

Many of the things that Dennis has talked about earlier are based on ITU-R recommendations on time and frequency broadcasts and their relationship to time scales. The tolerance between the UT and UTC are based primarily on recommendation ITU-R, TF460-5, which was established first in 1970 and modified in '74, '82, '86, and '97—we do a lot of modifications sometimes, to the 0.9 second difference between UT1 and UTC. These recommendations, opinions, and other things that the ITU establishes become ultimately established in legal facts in the various member states. These also regulate international treaties and other things relating to frequency spectrum and services used internationally. Consequently, UTC is in a number of other recommendations relating to the use of UTC frequency; the use of the term "UTC," what does it mean, and how do you establish that internationally; how do you compare these international time scales and other time scale notations; and a lot of other things that are looked at recommended by the ITU-R.

The way the procedures work within the ITU-R is they first establish a question to change, regulate, modify, or add some type of recommendation that may affect a number of these different treaties and things that are related to the ITU-R. Once these are studied and the questions are answered, these may end up in recommendations. These types of recommendations were first studied, agreed to, and looked at by many people before they were established. The recommendations and changes to them are also based on different studies that may last a number of years and examined by a number of different people.

From last year's result of many of these questions that are being asked that Dennis just went through, a new question was established on the future of the UTC time scale. If you were to consider going through a different time scale, that might affect time and frequency coordination and broadcast worldwide. These need to be accommodated in these types of recommendations. So a question was established last year as to what are the requirements if we change these recommendations. Whom does it impact? Does it make any difference? What are the present and future requirements for this tolerance? Do some of these changes make sense in the terms of the different systems, organizations, and legal bodies that may use them? Does the current procedure essentially satisfy everybody or should an alternative approach be adopted? These kind of general questions were asked last year.

After this occurred or around that time, the issue also raised in the consulting committee for time and frequency and other scientific bodies resulted in the Director of the BIPM writing a letter to the Secretary General of the ITU, who presides over the ITU-T and the ITU-R. The letter said that if these types of changes were to be contemplated, the ITU would need to take them up, actually incorporate them, and put them into effect. So as a result of this, the issue seemed to be a little bit more urgent than the normal method of studying the question for several years and ultimately coming to a conclusion. So this year, a special repertoire working group, by correspondence, on the UTC question was established. These are members:

I am fortunate enough to be the chairman of this group which is going to work this issue. We have adopted a plan of action of how to attack this. Since we are not exactly sure how much of an impact this is going to have and how much reaction we are going to get from the telecommunications, radio industry, and the scientific communities, this is a preliminary plan to at least assess the situation, see what might be necessary in order to fully address this issue, and establish a new recommendation or lack of recommendation.

The first step is that the Director of ITU-R will be sending a letter to the member states and section members within the ITU saying that this group has been established, what the basic plan of action is going to be, and what we are going to be doing. This is the usual formal step for the ITU to establish these types of groups and study plans. We had hoped that would have been out by the end of this month, but it is still not out yet, so it is still in the first step. Once that is done, then the participating organizations of sector members or member states would be then be identifying points of contact who would work with this special group to address the issues and assess the impact, or lack of impact, or changes that might be necessary to coordinate. We would then provide additional material on the question, distribute that, and begin the process of actually doing the study.

We're now in the fourth step, and the first step really hasn't occurred yet of introducing this question and our intentions to study this problem and address it with the various member states and organizations involved at this meeting. So we have accomplished one of our tasks already. During the time after the letter comes out and this discussion here, we will be collecting statements, comments, and studies that may have occurred already from the various agencies to incorporate those into a database or a library of information to base the studies on.

The next step would be to conduct a coordination meeting with the various member states or organizations and participants at the EFTF that will occur in France in March. Hopefully, we will be able to get enough information by that time to at least try to size the magnitude of the problem. It could be that nobody cares and nothing happens. Or it could be that everybody cares and we are covered up in information. We really don't know yet. So we would be able to assess the impact agencies that want to participate in the study and in the study group. Then we can discuss and try to coordinate what really should be what I anticipate to be the final plan of action to be formulated at that time. Exactly what we need to do, do we need to do certain studies? Do we need to do simulations? Do we need to coordinate with different agencies? Or exactly what needs to be done? We would hope to compile the results of that at that time and report back to the next working party 7A meeting, which will occur in May in Geneva next year, so that we may either finalize the issue or formulate a new plan of action and try to determine how long it's going to take to resolve this issue and come to closure on it.

So basically that is what we are working to right now. The working method for this is still being established as well. We would hope to establish a contact point at the ITU for e-mail or providing of material through their e-mail server that they have there. That has not been established yet. So at this time, I would offer up – I hesitate to do this – my e-mail address at the ITU. Any material sent to me by participants who would be participating in this, or representatives of member states, sector members, or scientific organizations could contact me. We would like to limit participation in the study group itself to representatives of agencies so that we can try to maintain a reasonably sized body. They could act as the focal point for their respective organizations and provide that to the study group.

Once the e-mail reflector is actually established, and hopefully that will occur within the next month or so, you may either send e-mails to me directly and I will distribute it to the rest of the working group, or later on you can subscribe to the e-mail. You can get involved and see what is going on in the formulation of the plan or submit inputs that you have representing

your organization. So basically, that is what we are up to. Thank you.

DENNIS McCARTHY: Thanks, Ron. The next member of the panel that we have here is Steve Malys from the National Imagery and Mapping Agency. And he's here to point out some of the concerns about making any changes in the definition of UTC. So Steve is here to argue for the status quo—just to more or less leave it alone.

STEVEN MALYS (NIMA): Thank you, Dennis. As we heard from Harold earlier, on the surface of the earth for a ship or any other navigator, 1 second of time is about a quarter mile. But if you think about a satellite in low-earth orbit, 1 second of time corresponds to about 7 kilometers of movement. So it's obviously very important that we account for 1 second very accurately. At the GPS altitude, which is higher than low-earth orbit, at that altitude a GPS satellite moves about 3 kilometers in 1 second. So leap seconds become very important, and procedures have been developed over the years to take leap seconds into account when they do occur. Keep in mind that over the last few decades we saw the evolution of time. Satellite systems have become operational over those last few decades and they are no longer experiments. GPS is obviously a very good example of operational system that we wouldn't want to have an interruption of service for any reason. There are other operation systems, particularly in the DoD, that the DoD depends upon very heavily. A good example of another satellite system would be something like the Defense Support Program, which looks at the earth for missile launches. You don't want to have an interruption of service to a system like that.

Another example is the operation that takes place in Cheyenne Mountain out in Colorado, the space surveillance operation that keeps track of more than 8,000 objects in orbit. It's a very operational system. There are strict procedures setup to handle things like leap seconds, and they have evolved over the years. Certainly, mistakes were made in the past and procedures have been refined. It is my experience that things have improved significantly. People have come to understand much better how to handle leap seconds to prevent the problem. We know, of course, that the Russian GLONASS systems has some difficulty dealing with that kind of operational system. It is my experience that within the U.S. DoD, we have become much better at dealing with leap seconds when they do occur.

So if there were changes to be proposed, and I'm just thinking of one of the cases that Dennis pointed out, if we were to allow the tolerance between UT1 and UTC to grow more than 0.9 seconds, what would happen? What would we actually have to do within the U.S.—DoD and other U.S. Government systems—to accommodate that? Keep in mind, for all of these satellites that are in orbit, we're doing orbit determination for these satellites in an inertial reference frame. We integrate the equations of motion in the inertial reference frame, but our tracking stations typically are on the ground. So our tracking stations are rotating with the earth, which means we need very precise knowledge of UT1. We routinely account for the difference between UT1 and UTC. That parameter is predicted on a routine basis. That is a very important piece of that transformation from the earth-fixed reference frame—it is the inertial reference frame.

So no matter what happens to time scales in the future, we need to account for the earth rotation rate because the tracking stations are most likely going to remain on the ground—at least, some of them will. The earth rotation is not going to go away from the perspective of doing orbit determination. So if we were to change current procedures, systems like GPS and other DoD systems would require some modification to the software. Remember these are operational systems, so a change of UT1 minus UTC graded on 1 second would mean there would have to be some effort initiated within each of these systems by somebody in the government who runs them. Most satellite systems are operated within the U.S. by the

government. Of course, there are commercial systems evolving now. You may have heard of the commercial imaging systems like ICONOS, which is operational. There are other commercial systems as well. I'm mostly referring to government-operated systems here. But there would have to be some initiation of software changes, documentation changes, other changes to the procedures that train personnel, and a significant amount of testing. It wasn't that long ago that Y2K was the big deal, and there was a lot of testing that went on. Even with all the testing that went on, there were still minor problems that occurred. But it's that type of thing that costs a lot of money to do, and there are strict interfaces set up among different satellite systems within the DoD. Those interfaces would have to be carefully looked at and analyzed.

Those are some of things that would have to start off if we were to make a change to the current procedure. Keep in mind that the original definition UT1 minus UTC, as we know it today, cannot exceed this 0.9 seconds. Well, many software systems were designed with that piece of information in mind. There are lots of software packages that treat that as a tolerance. The software will not allow UT1 minus UTC to be bigger than 1 second or it declares that there is a problem of some kind. There is a lot of range checking on parameters that go across different interfaces. Well, today these interfaces have this limit imposed in it. So it is similar to the problem that Dennis mentioned where many systems that broadcast UTC parameters have a limit of 1 second. This is another manifestation of that same kind of problem. These interfaces would have to be changed to accommodate something greater than 1 second.

So really, this is really a practical argument for keeping things the same. If we wanted to make changes, it is going to cost money. Like any good government institution, it is tough to change something once it gets institutionalized and operational. There would be money involved to the U.S. taxpayers, and other countries that run systems like this would have to allocate resources to make changes. Of course, experimental systems or systems that are just being designed now would be easier to change. That is mostly the operational system that I am talking about here today.

The typical procedure to change an operational system is to first obtain a rough order of magnitude from the contractors who are working with these systems. People who are involved in those systems will present a request for change to some configuration management board. If it is approved, there would have to be funds identified to go and change it. Believe it or not, even for a little thing like changing a tolerance from 0.9 seconds to something greater, you need to go through this whole process for an operational system. We would do all of that for no identifiable benefit. It would just be another way to handle the difference between earth rotation rates and some atomic time scale. There would be no improvement in accuracy that I have been able to identify. It would be just be another way of handling a procedure different from what we do today. That would be difficult to sell. If you are going to argue for making a change to one of these systems, you have to explain to the people who manage the funds for those system why they should do this. That would not be an easy argument to make because there is no identifiable benefit to any of these operational systems. It's just a different way of handling it. That is really the practical side that I am here to talk about today.

McCARTHY: Thanks, Steve. That is a real concern, one of the big issues.

Now I would like to open this for discussion. Wlodek, did you have something that you would like to say?

WLODZIMIERZ LEWANDOWSKI (BIPM, France): What I would like to say about this issue is that the BIPM does not have an official position on this issue. We are just taking calculations, computing UTC. We do not have a specific point of view or expertise to express ourselves on the issue because we do not have touch with the users and so on.

But I would like to make some comments about the possible use of TAI, because during CCTF, there was some discussion in Europe on this issue and some exchanges on this matter. After the last CCTF, about 2 years ago, our director wrote a letter to the operators of Global Navigation Systems informing them that if they have any troubles with UTC because of leap seconds, the suggested alternative is TAI. That is fine. If they use TAI for internal time scale systems, I argue with this.

But what worries me is that this letter is maybe not expressing as clearly as it should that the use should be limited only to such internal applications. I also saw in another document of ITU somewhere that TAI was suggested as an alternative to UTC for much broader applications. That worries me because this means, already having UTC, a legal time scale, we are suggesting introduction into civil life another time scale, TAI, which does not have legal meaning. But because of this discussion about leap seconds, some people begin to say—and this happened at the last CCTF—we in fact have a time scale that does not have leap seconds, so let's use it. But this is a problem. Because if people begin to use TAI for civil applications, which will be apparent and visible to the public, that will be a problem because we will be going to two time scales and that will lead to mistakes and possible disasters even. Because now the difference between two time scales is 32 seconds.

For example, on BIPM's Web site, we can see making two time scales, UTC and TAI. That worries me a little bit, because many people go into this Web site and they ask what the matter is and what time is it. What should I put my watch on, UTC or TAI? Which is the right time? In fact, the right time is not UT1, it is UTC. We should not make mistakes with TAI time. TAI is something else. In fact, TAI, I should say, is a UTC system time. It is an internal time scale to generate the final, official, legal time scale for the world which is UTC. So what I would like to point out, in summary, we should not go too quickly to TAI as an alternative because we would go into some big trouble. When I spoke about this issue with some people, they said that GPS time does not have leap seconds and people are getting GPS time. In fact, what I know of this, according to my experiments, GPS users don't use GPS time. GPS time is an internal time scale to the system. GPS users are using UTC(USNO) as broadcast by GPS so they use the right second.

McCARTHY: We often have that question about GPS time. People often think they're using GPS when they are not really using what is strictly defined as GPS time. They are using UTC, but they call it GPS time. Demetrios, if you could just briefly say something about URSI. Demetrios conducted a survey of an URSI group to give its opinions. If you could just say briefly what the results of that survey were.

DEMETRIOS MATSAKIS (USNO): You probably know this too. A lot of times, people turn their GPS receiver the wrong way and we get a phone call on why their receiver is 13 seconds off. That's an easy problem to fix. We did a survey—I actually talked about this a little bit at the last PTTI when the survey was in progress. It was under the auspices of URSI, but I tried to send it everywhere. I asked people to distribute it around, and I got several hundred replies. The committee prepared a final report, which we sent to everybody who sent us a reply. If any of you want it, we can send it to you. We set up a chat group to talk about the problem after the report went out. The computer got wiped out by a virus, we believe, about 2 weeks ago, and unfortunately, it was not correctly backed up. We recovered most of what we had, and I want to give it to Ron Beard. I'll give him all of the comments that people made about the report and after the report.

BEARD: If you look at the international community and the people who might be involved in this, it would get extremely large and complicated.

MATSAKIS: I made some notes and but did not come prepared to talk. Typically, the majority was against the change. Most of the people I got were complainers who didn't like the change. That's typical: when you say you want to do something, those who are in favor don't say much about it. When you look at why they were opposed to it, most of the people were opposed to it for reasons that were not related to money or anything practical. Steve was one of two people who came in with a practical objection. They both were the same, having to do with the expense of going over codes for large, expensive systems.

But the greater tone was a lot of very strong, sometimes emotional, people who said, "don't mess up our clocks." But there was nothing religious that I got, which was a bit of a surprise. I didn't go out of my way to contact religious leaders. I got one opposition from Saudi Arabia, and I asked him why; and the answer was he was concerned about amateur astronomers. And that was one class of user, amateur astronomers who cannot get the number of leap seconds or want to know how they can point their telescopes.

That was along with the other people who were giving reasons why you just don't want to have time going off. There was a problem with the NIST WWVB. When they broadcast the difference between UT1 and UTC, they only have a fixed area in their format. So that will eventually fail, and quite quickly. Any user who is getting that correction off of WWVB series will run into troubles. They don't know how many people, if any, are using that system, but they may find out if this thing happens.

So those are all the comments I can make just now concerning the notes I made on this.

THOMAS CLARK (NASA Goddard Space Flight Center): A couple of things that I want to make comments on relate to Dennis's comments earlier. First of all, just so you all are aware, of course, UT1 is an astronomical definition of time. The current arbiter of astronomical time is VLBI observation techniques. That comes through programs in this country from NASA, namely my program and Dennis's at USNO.

One of the things in talking about the parabolic type of tidal model that was not included in that, which is one of the things that concerns me, is that in addition to the predictable tidal terms there are a series of essentially random-walk phenomena. The recent El Niño that happened, the transition from El Niño to La Niña caused a sundial error of about 5 milliseconds. It happened to be about 3.5 milliseconds on one side and then 1.5 milliseconds as it recovered into the other. So the peak-to-peak range was about 5 milliseconds. So there was this random-walk curve of 5 milliseconds due to one discrete, albeit couple-year-long weather events on relatively short times. Those happened and it essentially has to be treated as a chaotic, stochastic noise process in terms of the clocks.

In addition, Dennis alluded to the decadal scale variations. Most of that comes from essentially climatological variations in our atmosphere and, more important than that, climatological variations in terms of the circulation of fluids inside the earth. Those have to be considered in all of this. They are not really predictive quantities, at least at our current level of knowledge. They have to be treated as a random-walk term. So I just wanted to make sure that people realize that it is not just the soli/lunar tidal drag of the earth that cause these effects.

I tend to come down on the side of let's not make changes based on the "it ain't broke, don't fix it" model. The current scheme keeps the attention of the populace. In many cases, the population, the human experience lives by astronomical events. I'm surprised at Demetrios's comments that he didn't get more in the way of religious types of input. I think it could be that URSI did not really solicit the opinions of religious and civil communities. They were soliciting scientific communities. Certainly, several faiths have events that are scheduled by

either solar or lunar events. Many of the fundamentalists that have those beliefs are also potential hostile enemies of more technologically advanced who don't want to have the feeling that Americocentric ideas are being crammed down their throat. So I would offer the caution that if changes are made, it could be viewed politically/religiously as being a very negative thing. I think that does have to be factored into all of this. We really need to think about it.

Ron Beard talked in terms of the ITU events. A couple of us were talking back here, and we are a little surprised that the ITU views this as a crisis event that is putting it into a fast-track status. I'm not sure that it is a crisis event. The civilization is certainly living with the current situation. Until the year 2600, when we hit a definition problem that the tidal effects make it so that it drags us into a 6-month refresh interval, not being adequate to maintain the current definition, there really is not a serious problem with the status quo. I hardly believe that making a decision that doesn't have an effect until approximately 2600 puts us into a crisis condition. So I guess I argue for maintaining the status quo.

McCARTHY: I would just like to offer one thing there. The decadal variations are what you saw in that simulation, so that's where that comes in. But it's not just 2600, because those decadal variations could force us to go to more than every 6 months insertions within the next 100 years. The crisis comment still stands.

BEARD: A crisis in the ITU—you are not familiar with the ITU time scale, obviously. ITU time and whatnot are very much governed by a lot of bureaucratic procedures. Putting it on the fast track means it will happen before the next decade happens, more than likely. So I did not mean to say that we were going to general quarters to address this by next month, certainly not. The issue was significant enough—perhaps I should have said—to put special focus on it. Perhaps shorten some of the time. But help focus the study and the highlighting of it to assess the full impact. As Steve pointed out, there is a significant impact on various section members, on costs of doing changes. Certainly, the status quo minimizes these types of status change cost.

However, some of the other issues are—let me say, many systems are using internal time scales rather than the official time scales in order to avoid leap seconds. GPS time, I think, is a classic example. Many other systems are doing this so that they can have a continuous time scale and do a lot of automatic processing that a discontinuous time scale does not permit. So if you look at the other systems that are coming on, the relationships and trying to bring all of these systems onto a common time scale have a significant problem by having a discontinuous time scale. One of the more significant decisions that is going to be made in the next year or so is the Galileo time scale. Its relationship to the other satellite systems, GPS, GLONASS, possibly other telecommunication systems on the ground that all these things need to be seeing this with, what time will they use? Will they use another internal time or will they use international standards? So that is part of the reason.

JUDAH LEVINE (NIST): I have just a few comments. First of all, David Mills and I are presenting a paper on the idea of simultaneously transmitting UTC and TAI over the Internet with the idea of addressing one of the solutions that you proposed of making TAI more available. That way you have both UTC and TAI sort of simultaneously. That doesn't take a position on the question, it kind of provides a solution that is available today without having to wait for the ITU to go into crisis mode. I think that is the first issue.

The second issue is that I have written to Demetrios about the finite resolution of our time services which would be broken if UT1 minus UTC were allowed to become bigger than a second. I don't think that is a big issue. We could redefine the time service transmissions to have a different resolution. I don't see that as a real issue.

When I was involved with Demetrios's questionnaire – I live in an astrophysical and astronomical institute, and so, of course, I had a long line of folks out the door discussing the astronomical and astrophysical religious fervor of "you mustn't change the time" and so on. But one of the things that emerged from that discussion is that there already is, of course, an annual term, because, when you talk about mean solar time, that is not a physical time. That's an average over a year. There is an annual variation in the time, which is like 15 minutes. Those folks have managed to cope with that 15-minute time without any difficulty at all. Of course, the whole leap second effect is a perturbation on this 15 minutes, and will remain a perturbation on this 15 minutes for quite some time to come. So I don't think it is really such a big issue as has been made, in a sense that you don't have to deal with this 15-minute question.

I guess the final comment I have is that I have been involved on and off in the definition of the Jewish religious calendar, which is locked to sunrise and sunset as defined locally. And we just use the tables from the Naval Observatory; there is no issue. We just define sunset, we look up what time it is, we print it on the calendar; and that is the end of it. It is just not a question.

WILLIAM KLEPCZYNSKI (Innovative Solutions International): I have a comment to make about UTC and GPS time. A lot of papers I've seen at some of the conferences, especially the ION conferences, are now referring to UTC(GPS). But really, they are referring to GPS time. So GPS time is neither UTC nor TAI, or even close to it because it,s off by about 12, 13 seconds or so. So that is the problem that Wlodzimierz was referring to when the difference between TAI and UTC is a whole integral number of seconds. The difference between GPS time and UTC is also still a whole number of seconds, and it has to be really kept in mind by the users.

THOMAS CELANO (Timing Solutions Corporation): I'd like to address a point that Steve made and I believe something that was missing in the previous talk. I think cost to the user community is an issue that is going to drive a lot of this. But I think that you missed a point in that there is a cost associated with how we do it now. You made a point of all the systems know how to deal with it now. But we install timing systems in a lot of places that literally shut down when the leap second happens. There is a cost associated with that that needs to be taken into account and if we're going to consider making the change. Because that cost would go away if we could become operationally continuous over these intervals. I don't think that we should use the changes in RFC that are going to be required to do all this stuff, but I don't think we should use the process of change as a reason not to do it. I think we need to be able to recoup the operational cost that we're spending now in testing and the loss of time during the steps in a more continuous fashion.

One thing that I think was missing in all of the options that you guys provided for how we deal with this is the cost associated with each one. I think Steve made that point very well. Different ideas are going to have different implications cost-wise, and one thing that produces cost is predictability. You had a couple options that had predictability, and if you have that, it really simplifies a lot of things operationally and it does reduce cost.

MALYS: One comment to that that I would like to add. Speaking of shutting down, one little anecdote I wanted to share: About 15 years ago, I was doing orbit determination on the Navy's Transit satellites. There was a gentleman working with me who did the prediction of earth orientation, including UT1. Well, every time there was a prediction of leap second, he would go on vacation because it was too stressful for him to handle. So I took over his job, and I owe him a thanks for introducing me to leap seconds.

HUGO FRUEHAUF (Zyfer, Inc.): I'm dressed in black to represent all the religions of the

world today. The three major high-profile religions that deal with time. First of all, in Judaism, as Judah has already mentioned, it is a matter of sunset, and that's taken care of, as he mentioned. In Catholicism, I know of no particular issues with respect to time, so I think that part of it is okay. In Islam, we're dealing with pointing to Mecca, and that can certainly be done without the leap second consideration. So there you have it, no mystery.

CHADSEY: One issue about the leap second and the timing for the religious community was from the people we've been able to talk to and get the information from. Most of them base it on the tables produced by USNO, or you can look them up in several books. Those are general tables, and it changes by a minute for about every 9 miles that you move in position, so there is a little bit of leeway there.

The people who are very orthodox believers say "Well, we need to worry about the refraction of the sun around the earth, and what about the mountains and things like this?" So a lot of those folks, through their religious upbringing and their training, have come to realize, "well, let's adjust it by 4 or 5 minutes," whatever their leaders have instructed them on. So they can account for these small variations of not only their location, but also the scientific fact of refraction of the sun and things like that.

So they're handling it and it is a minor problem for them. The major problem is more for the scientific and the communications industry. The costs of it are going to be ridiculous whichever way we go.

ROBERT NELSON (Satellite Engineering Research Corporation): The principal difficulty with the leap second is the operational problem that it presents to complex timing equipment. So, therefore, I would speak to eliminating the need for the leap second and continuing a time scale such as UTC, which means continuity with the present civil time scale. The difference between UTC and UT1 can be applied mathematically by those people who are best equipped to understand it, who are the celestial navigators.

I think history can provide us with a guide. What we are facing today with the atomic clock technology is that we have a paradigm shift. In the 14th century, when mechanical clocks first became possible with the invention of the escapement, they were used to ring church bells. It introduced to the public perception of time, for the first time, the notion of an equal hour rather than an unequal hour.

In the early part of the 19th century, astronomical ephemeredes were constructed with apparent time as the argument, instead of mean solar time. But when pendulum clocks advanced to the state that they could reliably provide a direct measure of mean solar time, then the equation of time, as Judah alluded to, with the maximum difference of 16 minutes between apparent and mean, was used in reverse. Instead of being used to determine mean solar time from apparent time, which was directly measured by the altitude of a star or the sun, it was being used to determine apparent time from the measured mean solar time as given directly by a clock. So I think the time has come in the 21st century, in modern society, to break the tie with the sun all together. After all, in a given time zone, the clock reading can be off from apparent time by as much as half an hour. We use the difference between Daylight Time and Standard Time regularly, which is a difference of a whole hour.

One of the options mentioned was the possible use of TAI. I think that was already addressed by the fact that it is different from UTC by 32 seconds. So if we went to TAI, we would have to change our clocks by 32 seconds. It is much like the calendar had to be changed by 10 days in 1582 when the Gregorian Calendar was adopted.

So I would propose then that instead, UTC be maintained continuously without leap seconds

and that, if necessary, a new time scale, which one could call "UT1C," could be provided, much as UTC is used today to provide the means of celestial navigation. Those people will need a direct measure of UT1. The difference between these two could be provided, for example, by coded signals, much as D-UT1 is provided now to give the difference to the nearest tenth of a second.